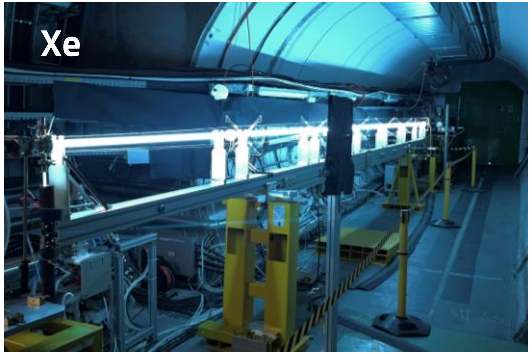
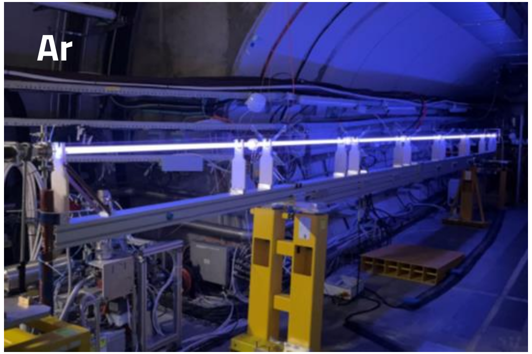
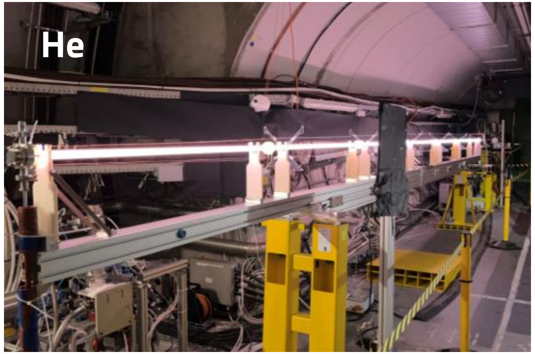
Measurements of the **electron density** in the **discharge plasma source**

Carolina Amoedo, Nelson Lopes, Nuno Torrado, Alban Sublet

AWAKE collaboration meeting, 4 Oct 2023







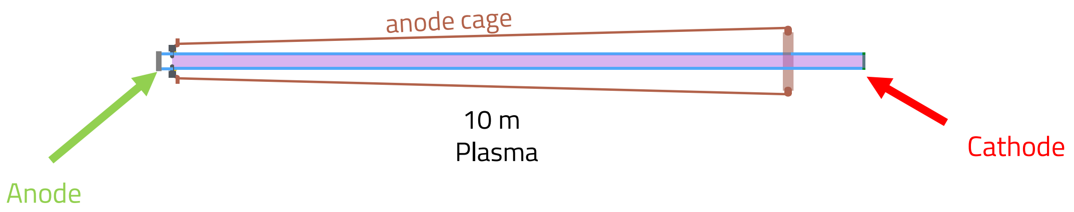
Special thanks to: P. Muggli[3], L. Verra[1], M. Turner[1], G. Zevi Della Porta[1,3], J. Pucek[3], M. Bergamaschi[3], A. Clairembaud[1], J. Mezger[3], F. Pannell[5], N. Z. van Gils[1], E. Gschwendtner[1], M. Taborelli[1] and *the AWAKE Collaboration*

[1]CERN, Geneva, Switzerland, [2]GoLP/IPFN, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal, [3]Max Planck Institute for Physics, Munich, Germany, [5]UCL, London, United Kingdom

Discharge plasma source (DPS)

Double-pulse arc discharge produced between two electrodes at the extremities of long dielectric tubes, filled with Ar/Xe/He at low pressure:

- The ignition pulse (up to 40 kV) establishes a low-current plasma (~10 A)
- The heater pulser allows for a **high current (up to 600 A)** to achieve the plasma density target



Scalable plasma sources R&D requirements

- Reach AWAKE nominal plasma electron density ($7x10^{14}$ cm^{-3}) ☑
- And longitudinal uniformity: 0.25% over 10 m
- Demonstrate scalability

DPS run with protons in AWAKE

Why? → unique chance to test an alternative plasma source between AWAKE run 2a and 2b

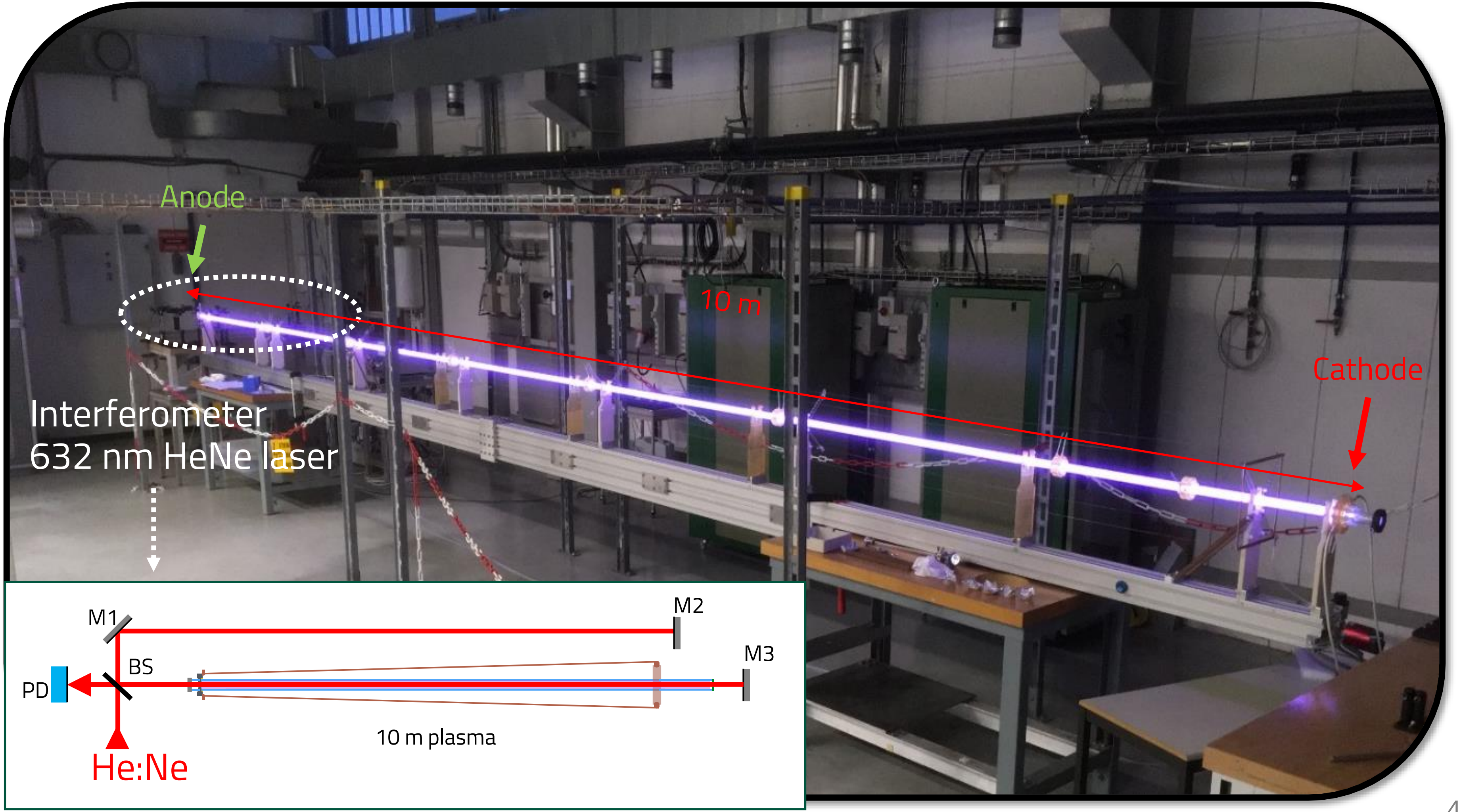
- Propagation of a proton bunch in a DPS plasma→ primarily to study **Self Modulation Instability (SMI) signature in the DPS** **(no laser, no electrons experiment)**

Parameter scan with lab interferometry

to assess plasma density for

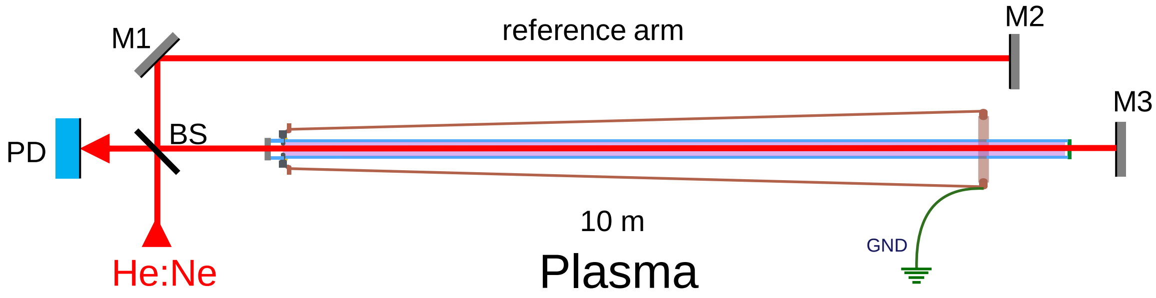
- 3 lengths (10/6.5/3.5 m)
- 3 gases (Ar/He/Xe)
- different discharge current (200..500 A)
- different pressures (8..45 Pa)

10 m single plasma, 24 Pa Ar, ignition+heating 500 A, ~30 us pulses


Anode
10 m
Cathode
Interferometer
632 nm HeNe laser
M1
M2
M3
BS
PD
He:Ne
10 m plasma

Longitudinally integrated interferometry

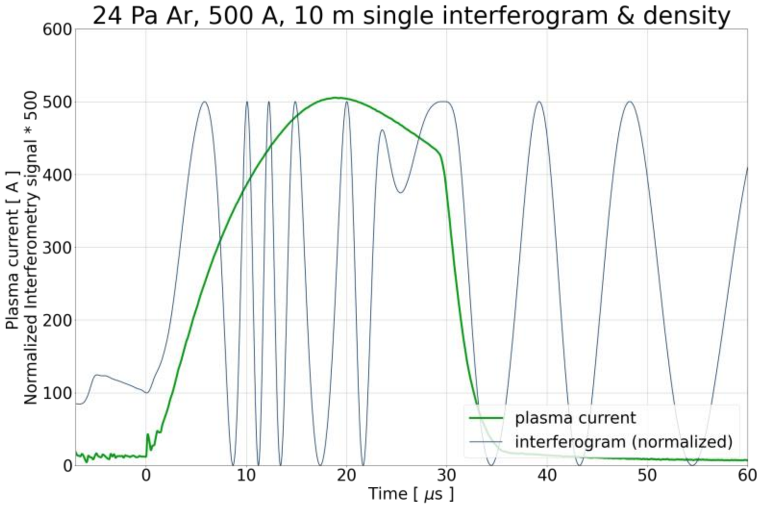
Preparatory lab work before the run



Plasma refractive index (n)

$$n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$

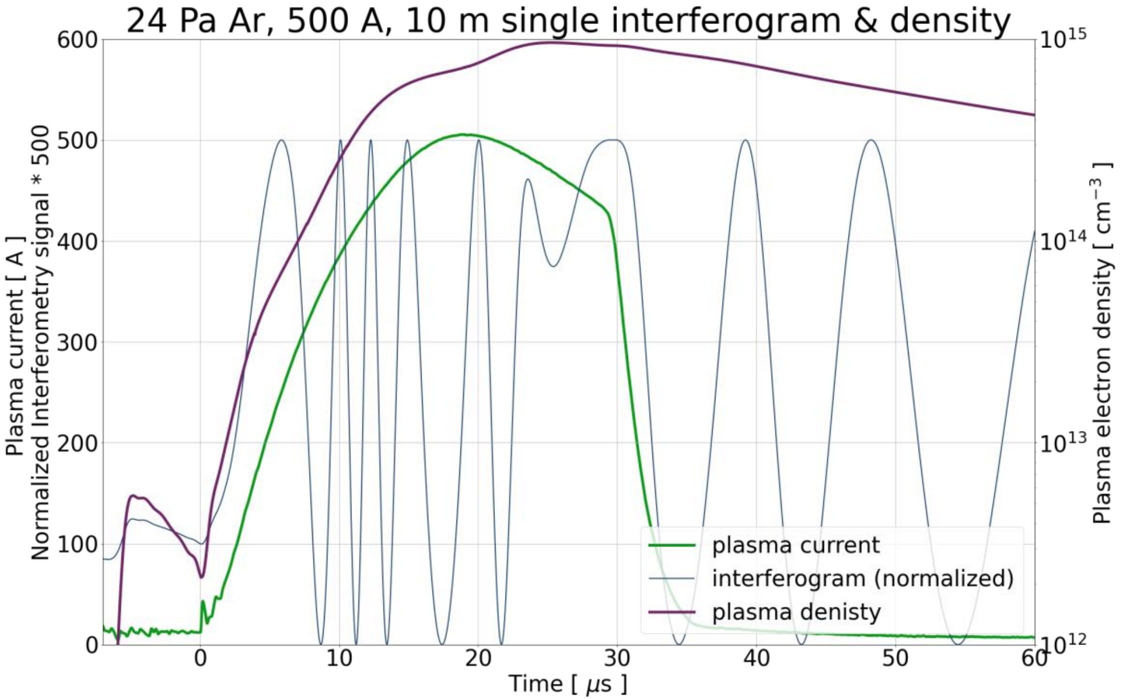
where ω_p is the plasma frequency → $\omega_p^2 = \frac{n_e e^2}{\epsilon_0 m}$



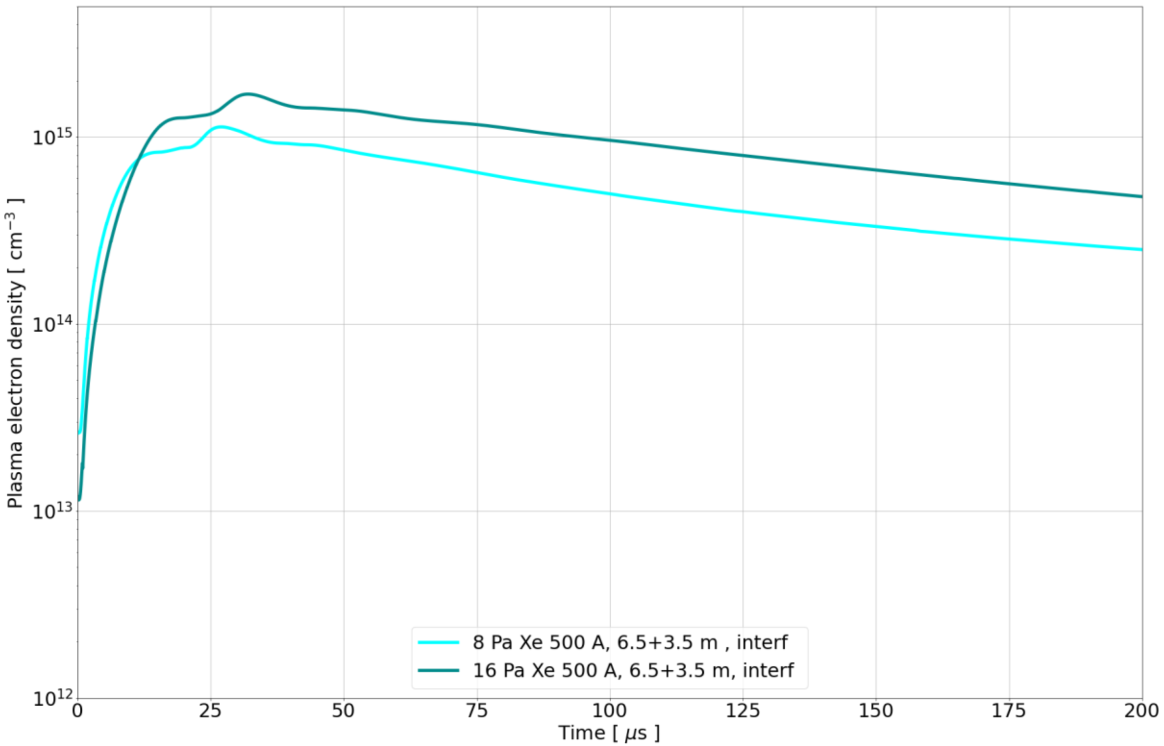
Phase shift ϕ_i added to the laser beam ($\lambda_i = 632\ nm$) by a plasma density n_e

$$\phi_i = r_e\ \lambda_i\ n_e\ L$$

where r_e is the classic electron radius ($r_e = 2.82 \times 10^{-15}\ m$) and L is 2x the length of the plasma



SUMMARY LAB INTERFEROMETRY



- **Xenon** allowed reaching densities **> $1x10^{15}$ cm^{-3}**

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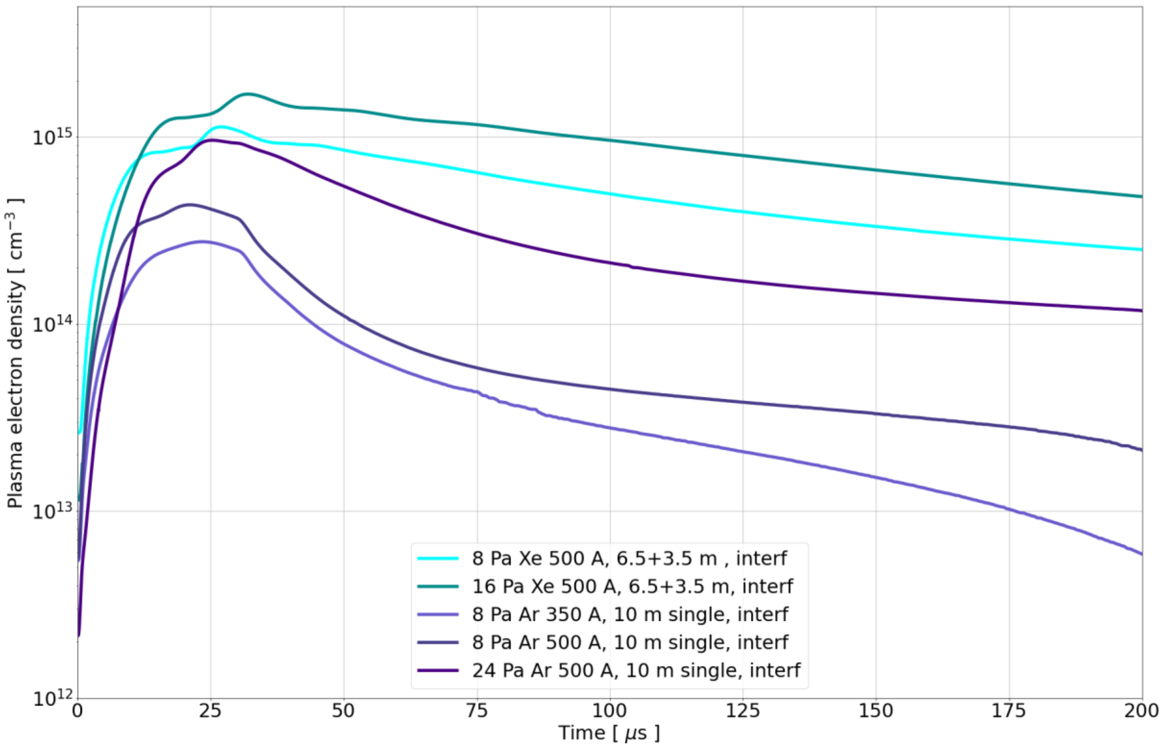

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→ well within **AWAKE nominal density** (7×10^{14} cm^{-3})

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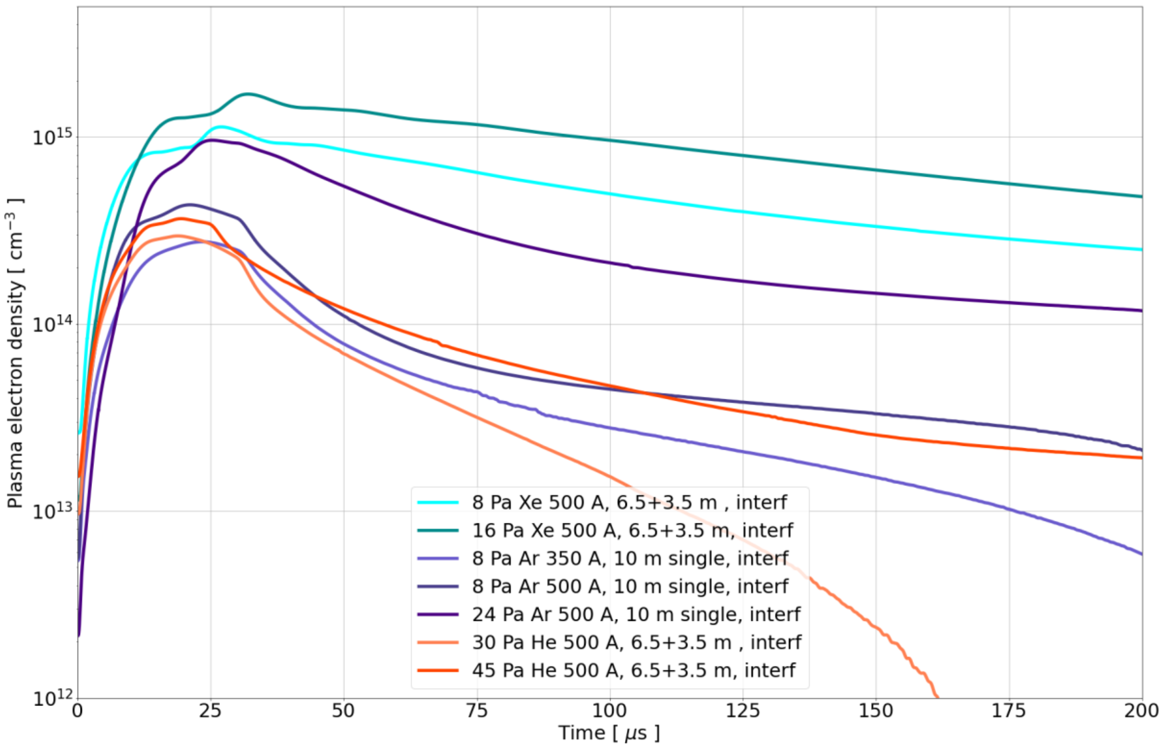

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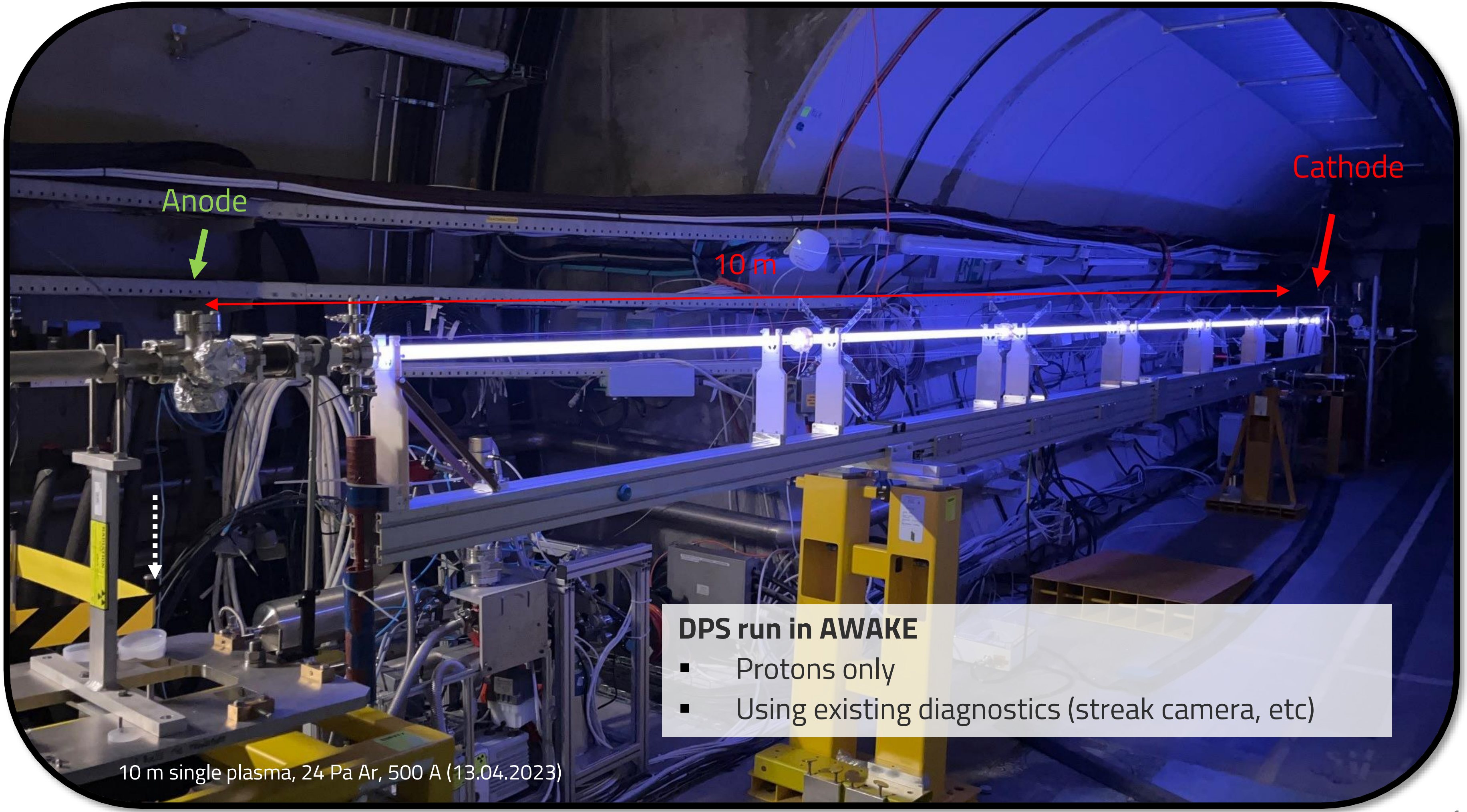
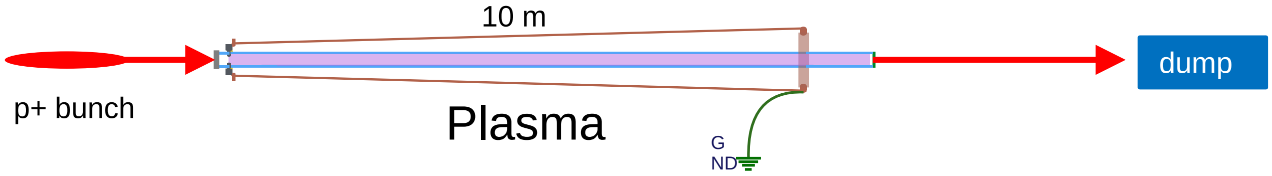
  → well within **AWAKE nominal density** (7x10^{14} cm^{-3})
- **Helium** tested for **significant ion mass** difference and its effects on self-modulation of the proton beam

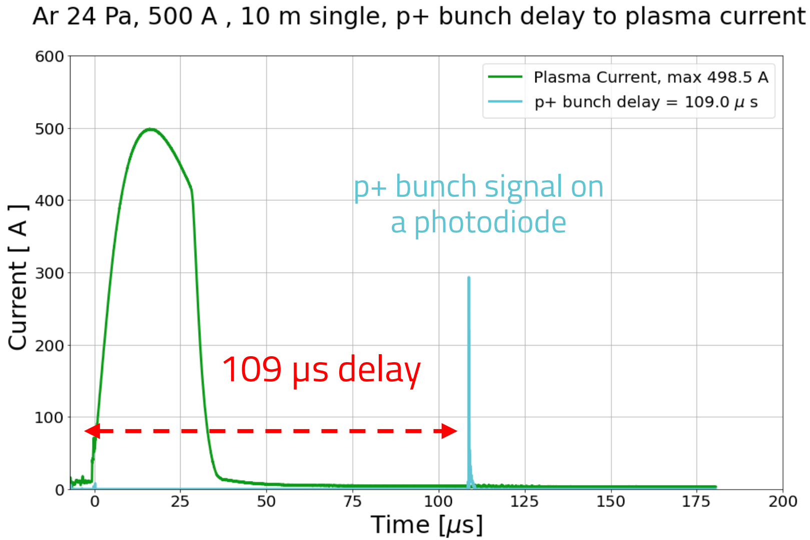


DPS run in AWAKE

- Protons only
- Using existing diagnostics (streak camera, etc)

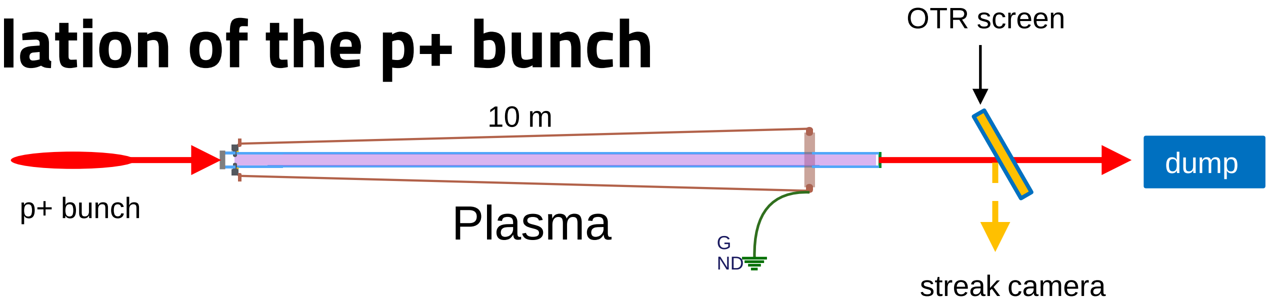
Synchronization of the p+ bunch with DPS plasma

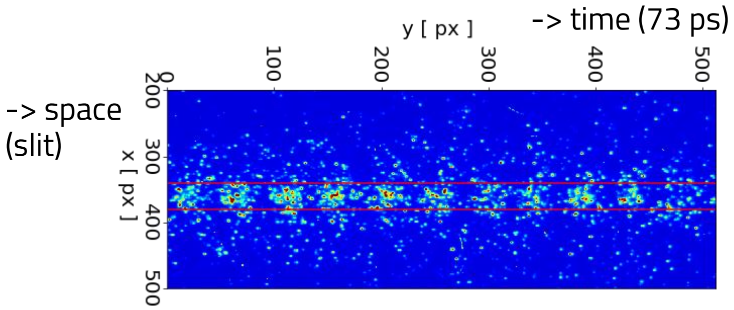




→ Change delay between current pulse and p+ bunch to access p+ modulation/plasma density at different time

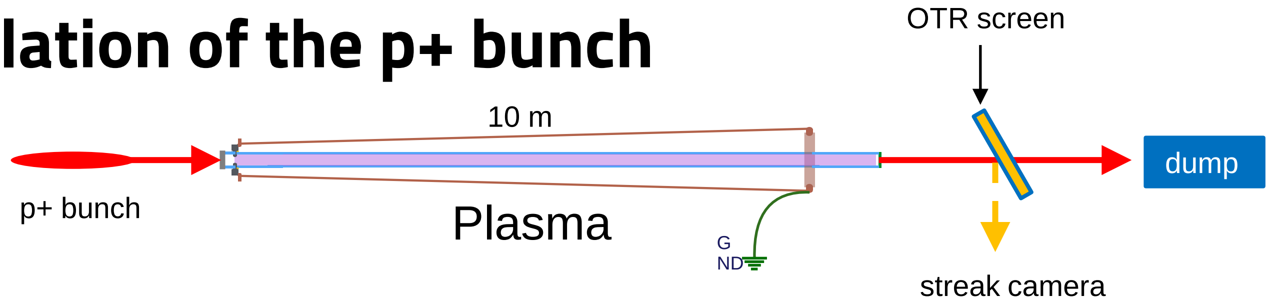
Streak camera
Modulation of the p+ bunch



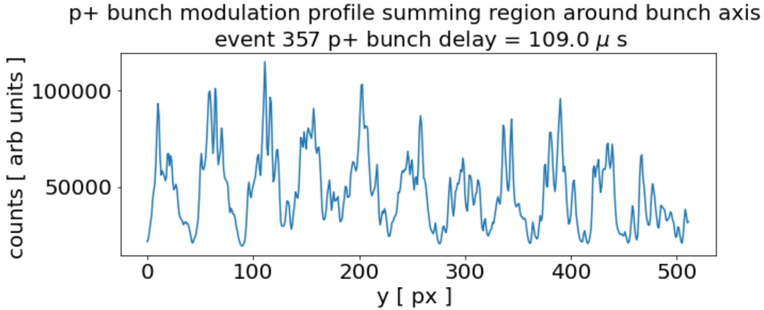


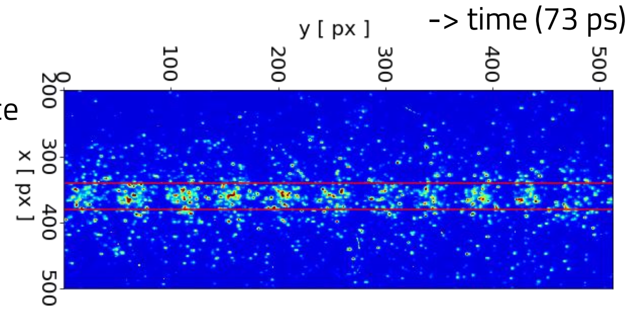
Time-resolved image of the p+ bunch charge density distribuition

Streak camera
Modulation of the p+ bunch



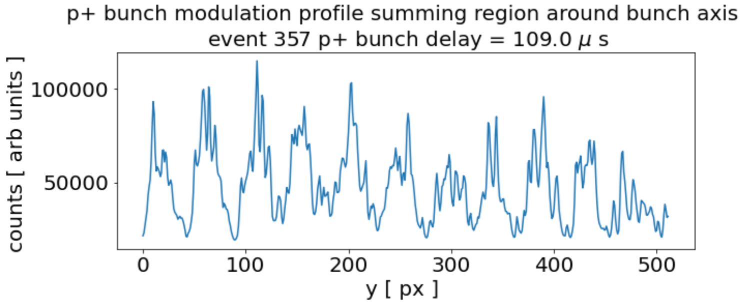
→ SMI observable with the DPS



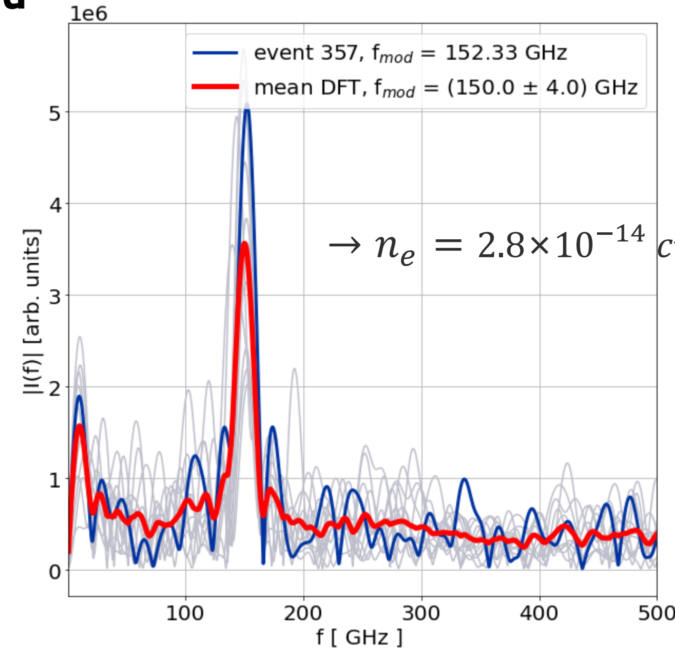


Time-resolved image of the p+ bunch charge density distribuition

Density measurement from f_{mod}



DFT



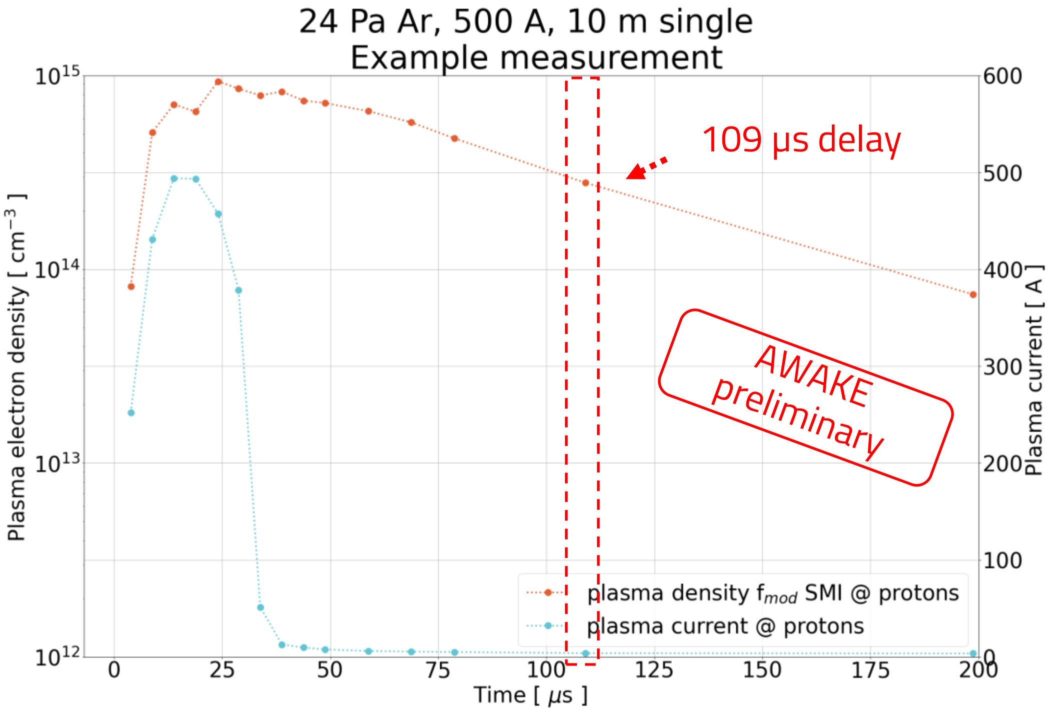
$$\rightarrow n_e = 2.8\times10^{-14}\ cm^{-3}$$

$$f_{mod} = 2\,\pi\,\omega_p$$

$$\omega_p^2 = \frac{n_e e^2}{\epsilon_0 m}$$

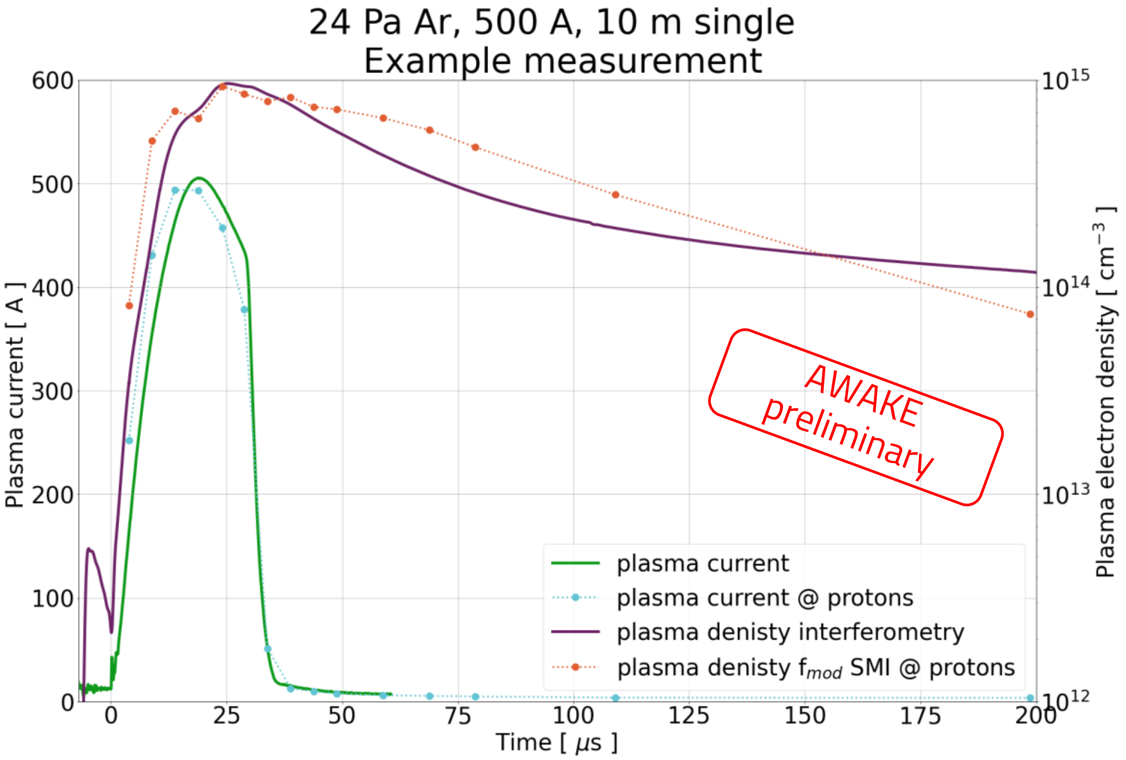
→ Modulation frequency proportional to plasma density

Delay density scan



- → Density profile over time from proton SMI
- → Interferometry lab measurements in **good agreement** density obtained with SMI

Benchmark lab interferometry plasma density with SMI modulation frequency



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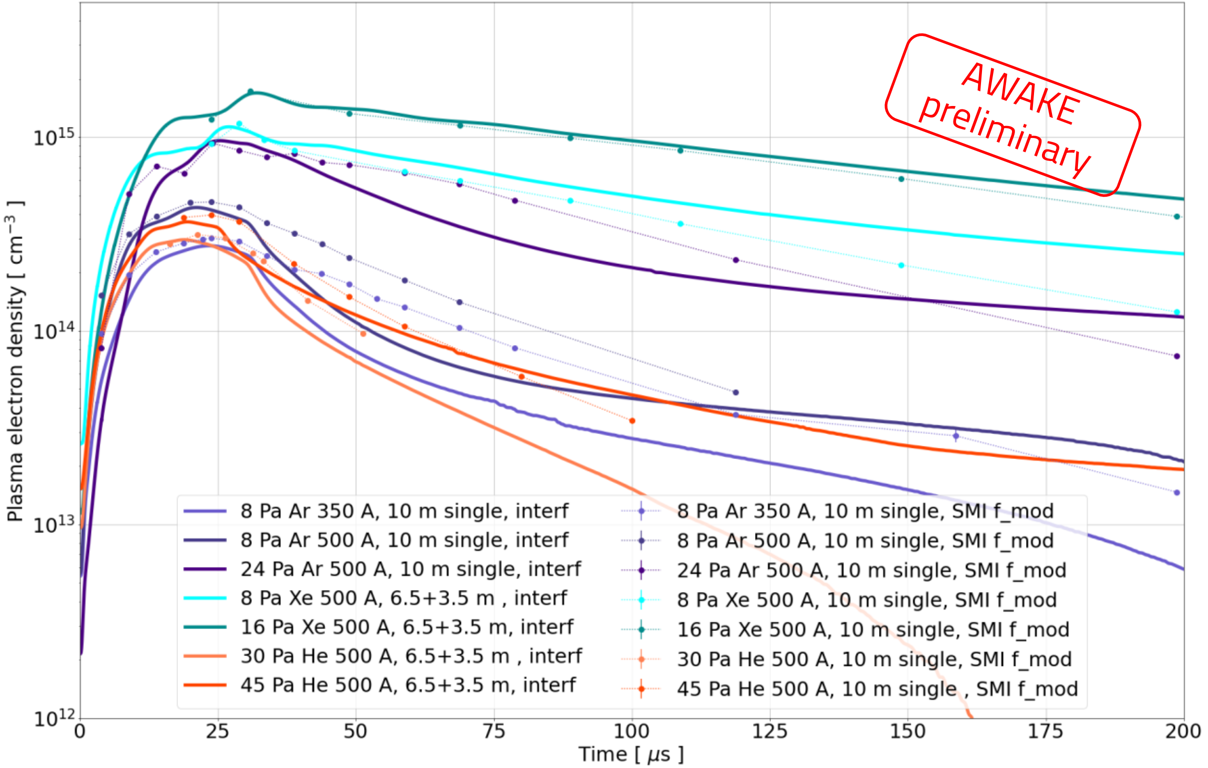

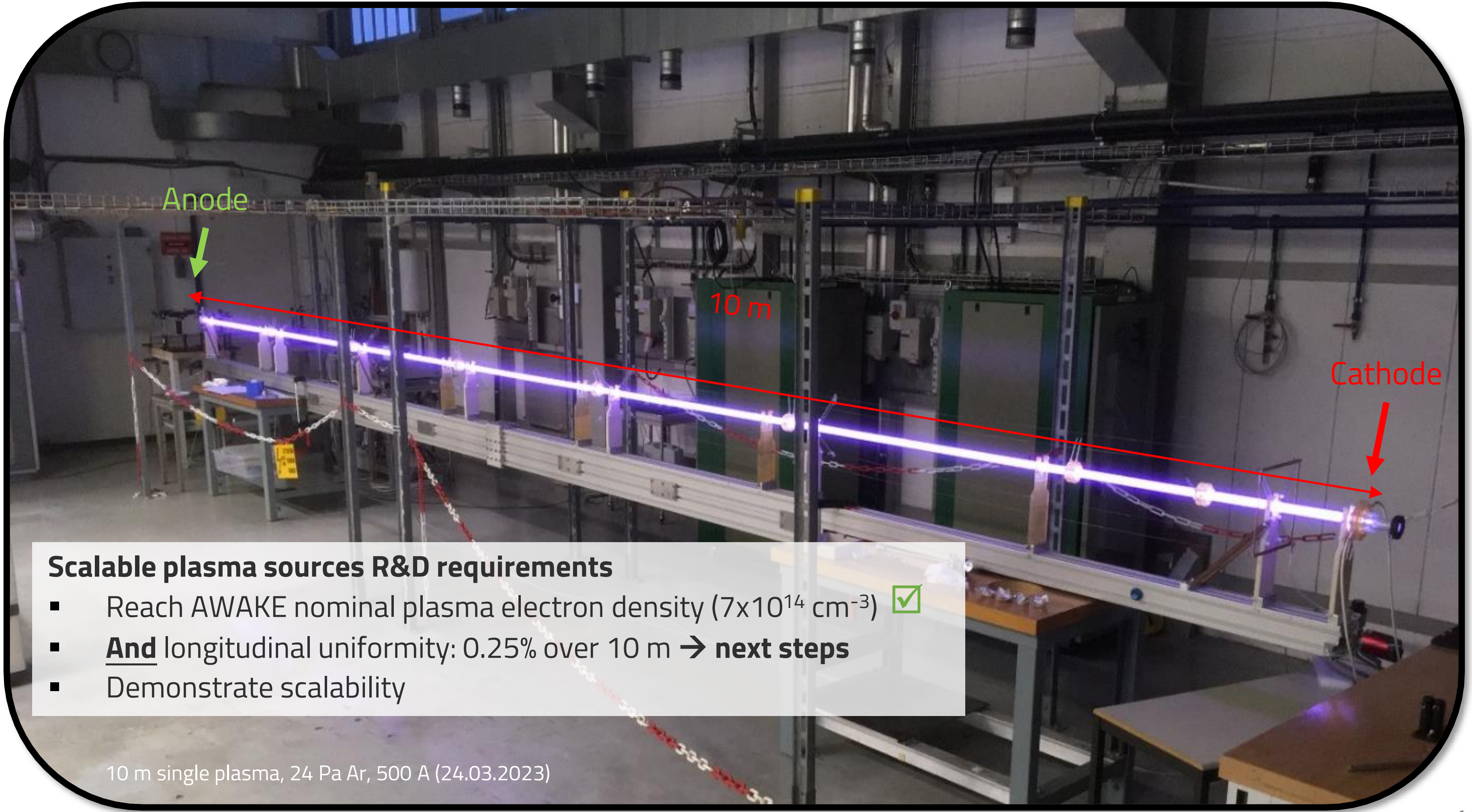

Scalable plasma sources R&D requirements

- Reach AWAKE nominal plasma electron density (7x10^{14} cm^{-3}) ☑
- **<u>And</u>** longitudinal uniformity: 0.25% over 10 m → **next steps**
- Demonstrate scalability

10 m single plasma, 24 Pa Ar, 500 A (24.03.2023)

Summary

- Achieved AWAKE nominal density, next steps to measure uniformity (Thomson scattering, µs cameras)
- 10 m DPS designed, built and tested in the lab: interferometry to measure longitudinally averaged density
- The self-modulation instability (SMI) signature was observed with the DPS
- Lab interferometry in good agreement with density from p+ self-modulation.
- Large operation range that allows to vary plasma density over wide range in different gases → study unique physics: plasma ion motion, Current Filamentation Instability with very high densities and wide bunches and plasma light, wakefied amplitude all along the plasma .